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14. ABSTRACT

This report concerns the development of a novel spatially modulated gain (SMG) electro-optical waveguides laser on LiNbO3 substrate. The main goal of this work is to implement an active LiNbO3 waveguide with the desired spatially modulated gain medium profile. We met this goal by implementing a Ti diffused erbium doped active laser waveguide that exploits optical Birefringence, pump beam standing wave pattern, and resonance optical pumping. In this report we discuss in detail the SMG waveguide design, SMG laser design / performance modeling, SMG laser fabrication, and measurement results.

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spatial hole burning, single frequency laser, waveguide, frequency tuning

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Spatially modulated gain (SMG) E/O tunable laser

Final report for research project: Award N00173-10-1-G034

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I. Summary

Numerous critical DoD applications call for a single wavelength, narrow line-width, rapidly tunable laser with a wide continues tuning range and a large output power. Such applications include: coherent optical receiver, CWFM lidar, RF/Optical waveform generation, etc. However, a laser that can simultaneously satisfy such attributes remains to be developed.

Table 1 summarizes the existing tunable laser technologies. A tunable laser diode has an inherently large linewidth and large phase noise. A bulk solid state electro-optic tunable laser has a low frequency tuning sensitivity. An Erbium doped $LiNbO_3$ waveguide laser theoretically can provide both the narrow linewidth and the higher tuning sensitivity. However, at present its single mode selection mechanism is based on DFB, which is not robust and also contains large optical loss. This mode selection mechanism limited its power to <1mW. Their long cavity lengths limits the voltage tuning range (<1GHz). It also contain gain spatial hole burning that contributes to optical RIN/ phase noise.

Table 1. Existing tunable laser technologies

Technologies	Advantage	Disadvantage
Tunable laser diode	Large tuning range Fast tuning speed	Large linewidth (~1MHz) Large optical phase noise Large RIN
Bulk E-O laser	Narrow linewidth (~10kHz) Low RIN Optical power (>100mW)	Poor tuning sensitivity (<30MHz/volt)
DFB Er:$LiNbO_3$ Waveguide laser	Narrow linewidth (~10kHz) Low RIN Good tuning sensitivity (~1GHz/volt)	Low output power (~1mW) Small continuous tuning range (<1GHz)

The goal of this project is to investigate a novel spatially modulated gain (SMG) electro-optic waveguide laser concept on a $LiNbO_3$ substrate(see Fig. 1).

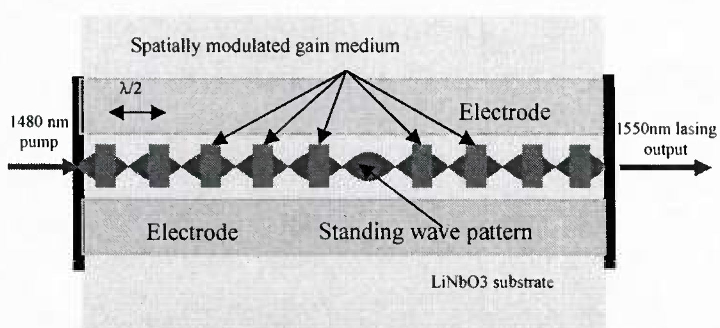


Fig.1 Single frequency waveguide e-o tunable laser with spatially modulated gain

The novelty of the SMG E-O waveguide laser is the **spatially modulated gain medium, that enforces single mode operation and eliminates gain spatial hole burning**. As shown in Fig. 1, the optical gain is periodically placed along the cavity where the standing wave pattern of the oscillating laser optical field is maximum. **This is fundamentally different from all existing F-P cavity lasers (Fig. 2a).** The spatial modulated gain medium will select a single

preferred laser oscillation frequency. More importantly, the spatial-hole burning associated with the F-P laser cavity, which is responsible for unwanted multi-mode oscillation and noise, is eliminated (Fig. 2b). The laser behaves like a quiet unidirectional ring laser. The SMG mechanism should yield robust single mode laser oscillation. The SMG mechanism do not need other inhomogeneous intra-cavity frequency selection mechanism (such as a DFB section or DBR). Therefore, the laser cavity can be made very short, which enables very large cavity Free Spectra Range (FSR) and consequently large tuning range.

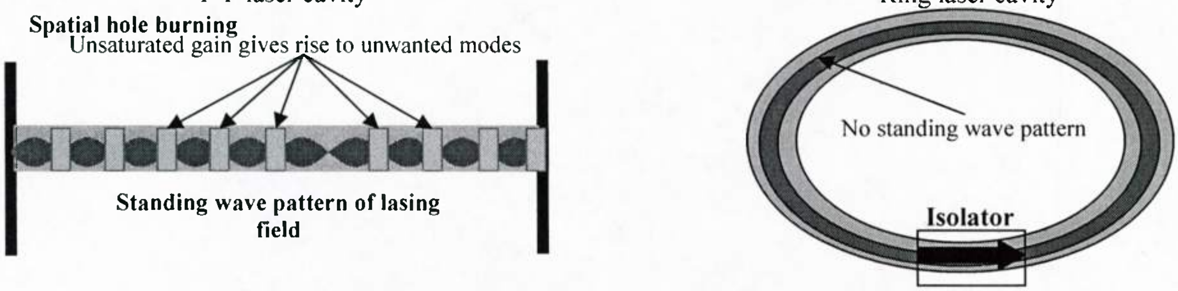


Fig. 2 F-P laser cavity (a) and uni-directional ring laser cavity (b)

The main goal of this project is to implement an active $LiNbO_3$ waveguide with the desired spatially modulated gain medium profile. We achieved this goal. In summary during this project we have accomplished the following :

- Designed and analyzed spatially modulated gain electro-optical waveguide laser on LiNbO3 substrate. In particular, we devised a novel approach of achieving spatially modulated gain by exploiting optical Birefringence, pump beam standing wave pattern, and resonance optical pumping.
- Developed the recipe for the SMG laser device fabrication and fabricated complete SMG laser devices (see Fig. 3) using Harvard University CNS clean room facilities

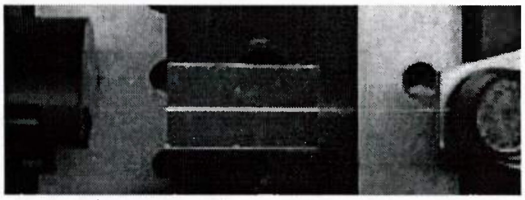


Fig. 3 Fabricated SMG laser device

- Comprehensively characterized the fabricated SMG laser devices:
  - Measured over 2dB/cm (with 90mW optical pumping) small signal gain
  - Measured small cavity loss (~2.2dB round trip)
  - Measured strong resonance enhancement to pump coupling (~18dB) to the laser cavity
  - Observed strong amplified spontaneous emission in the laser devices

However, at present the lasing performance of the fabricated SMG laser devices are limited by available single frequency pump power

II. SMG active waveguide

In the project we carefully studied four approaches for introducing spatially modulated gain as suggested by the original proposal. We focus on the last approach for SMG waveguide implementation.

2.1 Selective Erbium implantation (Fig. 4a).

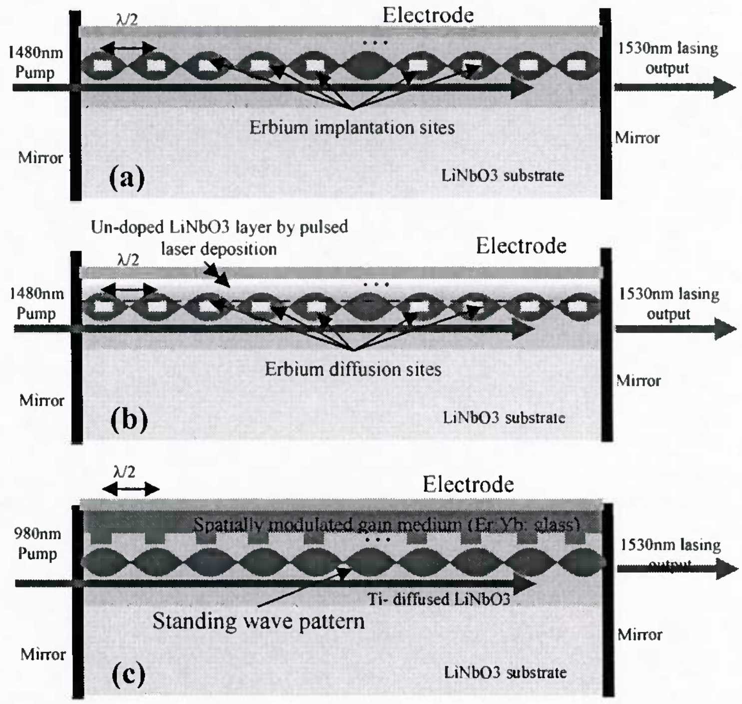


Fig.4 Initially considered approaches for implementing spatially modulated gain. (a) Selective erbium implantation; (b). Selective erbium indiffussion (b) Grating coupled gain/electro-optic medium

In this approach erbium ions are implanted selectively into a $LiNbO_3$ waveguide via an implementation mask patterned over the $LiNbO_3$ substrate. The locations for the implantation sites are coincident with the maximum of the standing wave pattern of the optical field. For example, for 1.55 µm laser wavelength, the distance between the adjacent implantation sites is 0.35 µm. The implanted Erbium sites are later activated by annealing.

We simulated the Erbium ion implantation profile to $LiNbO_3$ substrate (see Fig. 5). We found that in order to get over 1micron deep penetration large implantation energy (MeV) is needed. In addition, we observed ~0.2 microns lateral extension, which is marginally exceeds the tolerance of the required gain profile (with period of 0.35 microns).

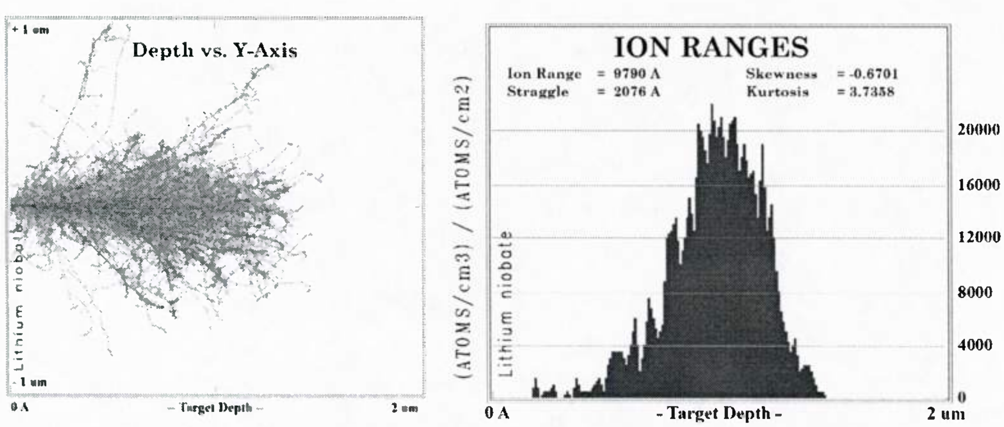


Fig. 5. Erbium ion implantation profile (3MeV).

However, our biggest concern is whether we can make a laser device using erbium implanted $LiNbO_3$. Through implantation, Erbium doping levels of ~ $1x10^{20}$ ions/cm^3 Erbium doping level [1] has been demonstrated in the literature. No degradation to the upper level lifetime and the emission / absorption cross sections as compared with the bulk Er doped $LiNbO_3$ crystals were observed there. In theory, these are sufficient to achieve over 1dB/cm gain. However, we cannot find any information on optical loss introduce by the high energy implantation. Erbium implantation of $LiNbO_3$ is a still material science problem. Further research is needed to realize high quality Erbium ion implanted $LiNbO_3$ waveguide that are needed for realizing laser and optical amplifier devices. This is a major risk factor. We concluded that even though selective erbium implantation is a novel technology, it is not feasible for realizing the SMG active laser waveguide considering the scope of this specific project.

2.2 Selective Erbium Indiffusion (Fig. 4b): Erbium ions are first diffused selectively to a Z-cut $LiNbO_3$ substrate, and then a layer of updoped $LiNbO_3$ is deposited to cover the Erbium diffusion sites by pulsed laser deposition. The diffusion sites are coincident with the maximum of the standing wave pattern of the optical field. However, this approach requires re-deposition of $LiNbO_3$ films after selective erbium indiffusion, which is not a mature technology. The re-deposition interface contains large optical loss, prohibiting laser operation.

2.3 Grating coupled gain/electro-optic medium (Fig. 4c). In this approach a grating pattern (or an array of trenches) is dry-etched over the waveguide. The locations of the trenches are only coincident with the maximum of the stand wave pattern of the oscillating optical field. However, This approaches requires a deep etch in to LiNbO3 substrate (>1 micron) in order to obtain large coupling between the optical field and the gain medium. Our study showed that the deep etching will add very large scattering loss, which is significantly higher than the optical gain (~1 dB/cm).

2.4 Pump beam defined spatial gain modulation (Fig. 6). The spatially modulated gain is introduced dynamically by **the standing wave pattern of a single frequency 1480nm pump laser beam** inside an erbium diffused optical waveguide. In order to align the standing wave patterns of the pump beam and the 1530nm laser oscillation, **the optical birefringence of LiNbO3 crystals is exploited**. As shown in Fig. 6, an x-cut LiNbO3 wafer is used. The polarization of the 1530nm laser oscillation is in the x direction (o-ray) as determined by the polarization dependency of the Er:LiNbO3 emission crossection. On the other hand, the polarization of the 1480nm pump beam is set parallel to the y-z plane (e-ray). The direction of the optical waveguide offsets the crystal z axis by an angle θ. By selecting a proper θ angle, the two standing wave patterns (1480nm e-ray and 1530nm o-ray) can be exactly aligned (see Fig. 6).

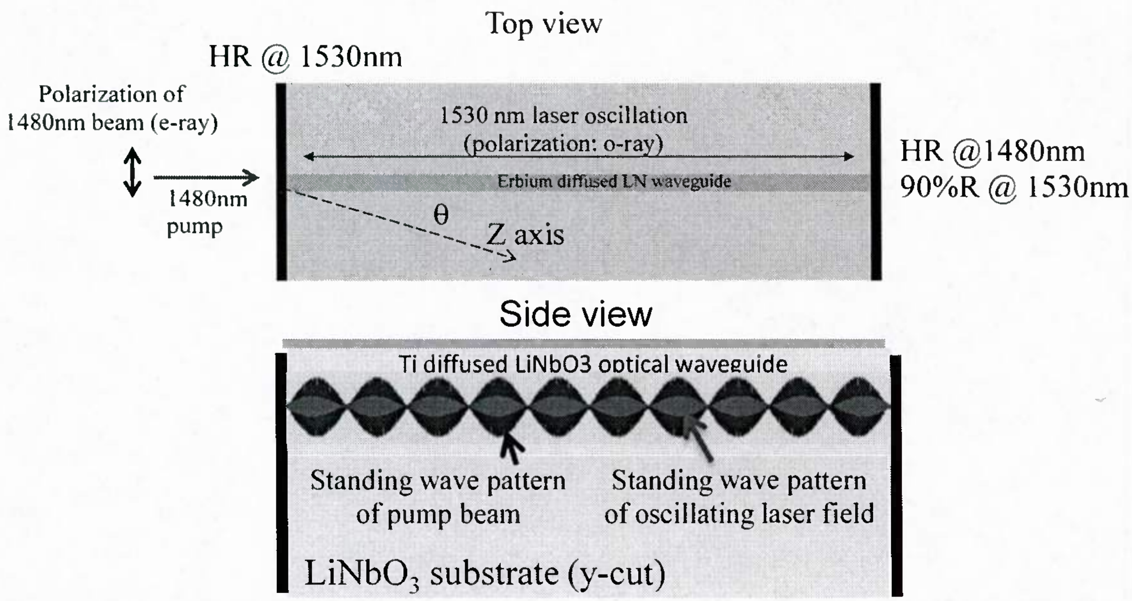


Fig.6 Dynamically generate spatially modulated gain profile using the standing wave pattern of the 1480nm pump beam.

For complete alignment of the two standing wave patterns (1480nm pump and 1530 laser oscillation), the refractive index of the pump beam should satisfy:

$$n = 1480 \cdot n_{o\_1530nm} / 1530 \qquad (1)$$

where n_{o_1530nm} is the refracitve index of the 1530nm ordinary ray, n_{o_1530nm}=2.21179. This requires the angle θ to satisfy:

$$\cot(\theta) = \sqrt{\frac{n^2 / n_{e\_1480nm}{}^2 - 1}{1 - n^2 / n_{o\_1480nm}{}^2}} \qquad (2)$$

where n_{e_1480nm} and n_{o_1480nm} are the refractive indices of the extraordinary and the ordinary waves at 1480nm wavelength. They are 2.13962 and 2.2135, respectively. As shown in Fig. 7, the desired waveguide orientation is a strong function the pump wavelength. For 1480.07 nm pump wavelength, the desired waveguide direction is 90 degrees relative to the optical axis. For 1482nm pump, the direction of the waveguide should be 78 degrees. It should be noted that for pump wavelength less than 1480.07nm, the right hand side of Eq. 2 became negative and it is not possible to match the standing wave pattern of the pump with that of the lasing wavelength.

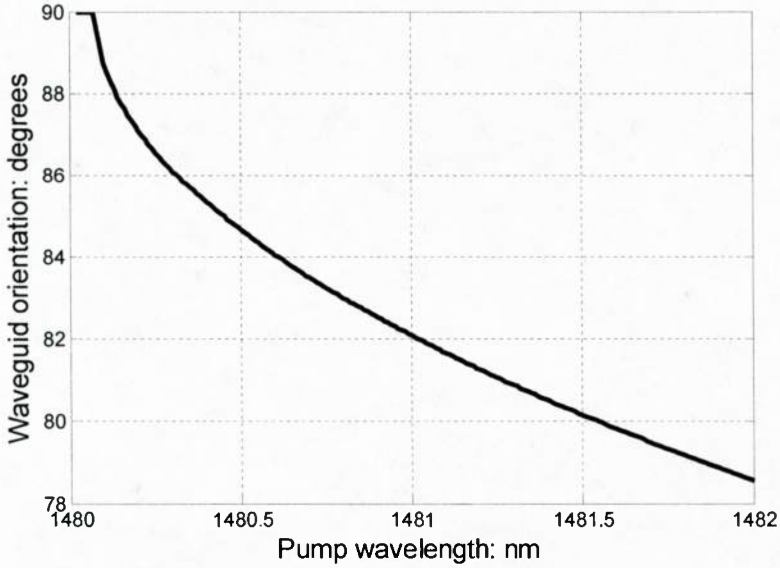


Fig.7 Waveguide direction vs. pump wavelength

This approach of realizing the spatially modulated gain profile by the pump beam has the following advantages:

- It uses erbium in-diffusion on LiNbO3 wafer, which is already a mature process.
- There is no need to artificially pattern a fine periodic structure.
- It is of low optical loss as it requires no physical perturbation to the waveguide.
- The pump beam and the laser oscillation mode can achieve almost perfect longitudinal and transverse spatial overlap. This shall help laser efficiency.

One drawback of this approach is that it requires a 1480nm single frequency pump laser, which generally have much lower power compared with a commercial multimode 1480nm pump laser diode. In addition, pump absorption along the optical waveguide reduces the standing wave ratio of the pump beam. For mitigation, the pump absorption length should be much larger than the length of the laser cavity.

Without adversely affecting the pump absorption efficiency, we will use a resonance pumping scheme (see Fig. 8), where the 1480nm pump beam is also set to resonate with the laser cavity. When the pump beam is set at resonance, the large pump absorption (>90%) even with very small round trip loss absorption of the pump (see Fig. 9) provided the cavity round trip loss is small.

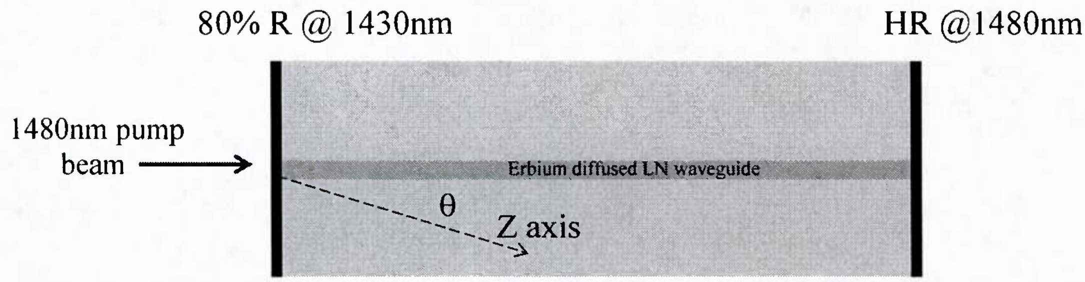


Fig.8 Resonant pump is used for retaining large pump beam standing wave ratio without hurting the laser efficiency.

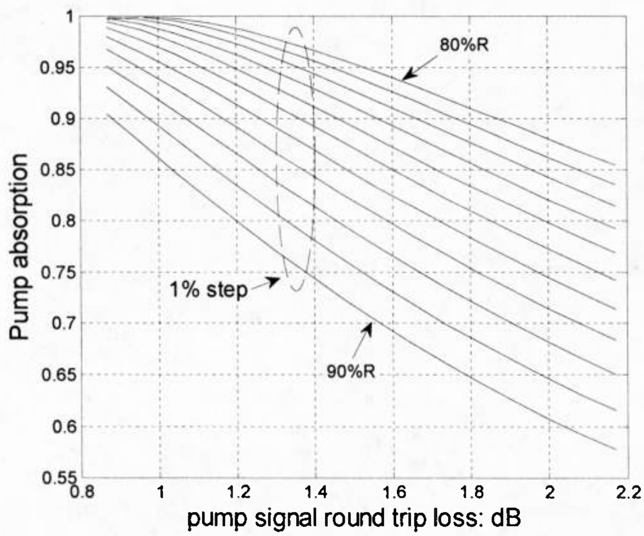


Fig. 9.Enhanced pump absorption with resonant pumping

III. SMG laser performance modeling

3.1 Threshold, efficiency, and single mode output power

We developed the following quazi two-level rate equations to model the SMG laser.

$$\frac{dN_2}{dt} = -\frac{N_2}{\tau_2} - \sigma_e \cdot I_m(z) \cdot (N_2 - N_1) + \eta_p \sigma_a \cdot I_p(z) \cdot N_1 \qquad (3a)$$

$$N_2 + N_1 = N \qquad (3b)$$

$$\frac{dI_m}{dt} = -\frac{I_m}{\tau_c} + \frac{\eta_L \cdot \sigma_e \cdot}{\tau_r} \int_0^L I_m(z) \cdot (N_2 - N_1) \cdot dz \qquad (3c)$$

$$I_p(z) = 4 \cdot I_p \cdot \sin^2 k_p z \qquad (3d)$$

$$I_m(z) = 4 \cdot I_m \cdot \sin^2 k_L z \qquad (3e)$$

where N_1 and N_2 are the densities of the Erbium ions in the ground and the excited states, respectively; $I_p\ (z)$ and $I_m\,(z)$ are the intensities of the pump and the lasing mode, respectively; ; I_p and I_m are the intensities of the forward propagating waves of the pump and the lasing mode, respectivelyη_p is the overlap factor between the pump optical field and the gain medium; η_L is the overlap factor between the lasing mode and the gain medium; $\sigma_e$and $\sigma_a$are the emission and the absorption cross-sections of the Erbium ions, respectively, and N is the density of the Erbium ions; τ_r is cavity round trip time, τ_c is the cold cavity decay time for a laser photon, and τ_2 is the upper level life time of the Erbium ions.

In steady state, the time derivatives in Eq. 1 should be zero. These gives:

$$\delta N(z) = \frac{\sigma_a \cdot I_p(z) - 1/\tau_2}{\sigma_a \cdot I_p(z) + 1/\tau_2 + 2\sigma_e \cdot I_m(z)} \cdot N \tag{4a}$$

$$\frac{\tau_r}{\tau_c} = 4\eta_L \cdot \sigma_e \cdot \int_0^L \sin^2(k_m z) \cdot \delta N(z) \cdot dz \tag{4b}$$

where δN is the inversion density, $\delta N = N_2 - N_1$.

The laser threshold should satisfy:

$$\frac{\tau_r}{\tau_c} = 4\eta_L \cdot \sigma_e \cdot \int_0^L \frac{\sigma_a \cdot I_p(z) \cdot \tau_2 - 1}{\sigma_a \cdot I_p(z) \cdot \tau_2 + 1} \sin^2(k_m z) \cdot \delta N(z) \cdot dz$$

$$\frac{\tau_r}{\tau_c} = 2\eta_L \cdot \sigma_e \cdot L \cdot N - \frac{2\eta_L \cdot \sigma_e \cdot L \cdot N}{\sqrt{\left(\tau_2 \sigma_a I_p + 1/2\right)^2 - \tau_2 \sigma_a I_p}}$$

$$+ 2\eta_L \cdot \sigma_e \cdot \frac{N}{\tau_2 \sigma_a I_p} \cdot \left[\frac{1 + \frac{1}{2\tau_2 \sigma_a I_p}}{\sqrt{\left(1 + \frac{1}{2\tau_2 \sigma_a I_p}\right)^2 - 1}} - 1 \right] \int_0^L \cos(2\Delta k_m z) \cdot dz \tag{5}$$

Using Eqs. 4 and 5, we simulated the laser threshold and efficiency. The parameters used for this theoretical study were summarized in Tables 2 and 3.

Table 2 Material properties of the SMG laser Ti:Er: $LiNbO_3$ waveguide.

Emission cross section : σ_e	$2.8\text{x}10^{-20}$ cm^2
Absorption cross section: σ_a	$0.2\text{x}10^{-20}$ cm^2
Erbium ion peak concentration: max(N(z))	$0.8\text{x}10^{20}$ cm^{-3}
Upper level life time: τ_{21}	2.8ms
Waveguide scattering loss (laser) α_L	0.2dB/cm

Table 3 SMG laser design parameters

Wafer orientation	x-cut LiNbO3
Waveguide orientation	y (90 degree to z-axis)
Laser length: *L*	2 cm
Laser waveguide width	6 microns
Waveguide cross section: A	~70 micron^2
Input side dielectric mirror	80% R @ 1480 and 1530
Output dielectric mirror	98% R

We use x-cut LiNbO3 wafer to realize the SMG laser. The laser waveguide in the y axis direction. The laser length is 2cm. The laser optical waveguide is defined through Ti diffusion (see Fig. 10a). The width of the Ti strip is 6 micron. This gives a mode crosssection of ~70mciron^2(see Fig. 10b). The laser input side has a dielectric mirror with 80% reflectivity and the output side has a dielectric mirror with 98% reflectivity.

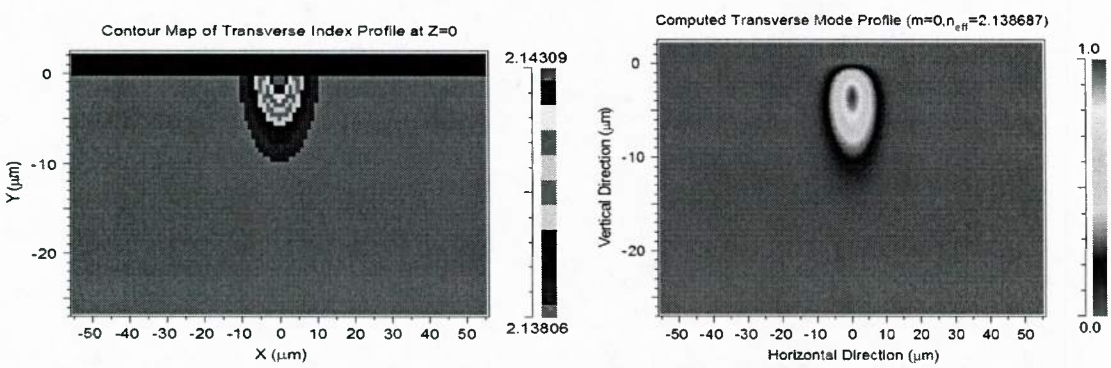


Fig. 10: Ti diffused optical waveguide. (a) index profile; (b) fundamental mode

Fig. 11 shows the simulated threshold pump power (inside the laser cavity) as a function of the cavity round trip loss. For a cavity round trip loss of 2dB, the threshold pump power inside the cavity should be ~8.3mW.

Fig. 12 shows the simulated laser output power vs. its input. The simulated laser slope efficiency is around 67%. Since Erbium doped LiNbO3 is homogeneously broadened and the SMG laser contains no spatial hole burning, the single frequency operation is guaranteed. The maximum single mode output power is only limited by the laser waveguide damage threshold. In addition, from the simulation, we also find strongly frequency selection mechanism due to the designed spatial gain profile (see Fig 13).

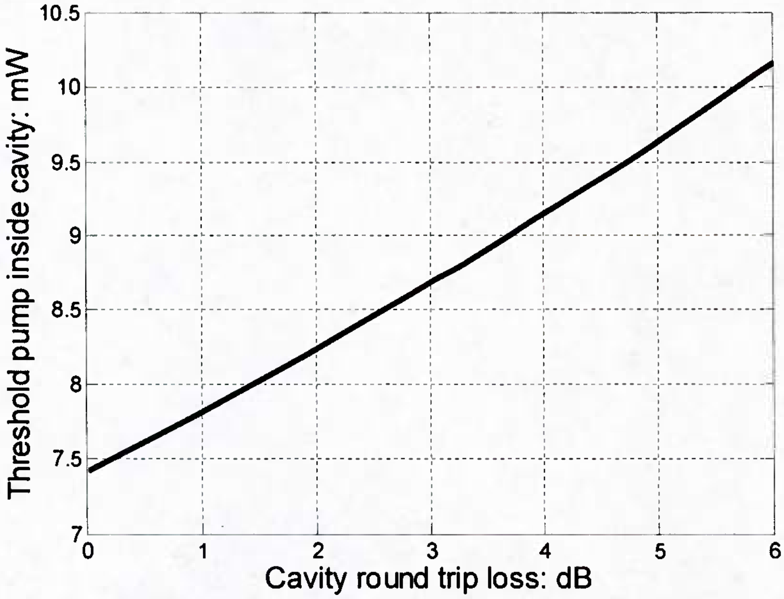


Fig. 11 Laser threshold vs cavity round trip loss

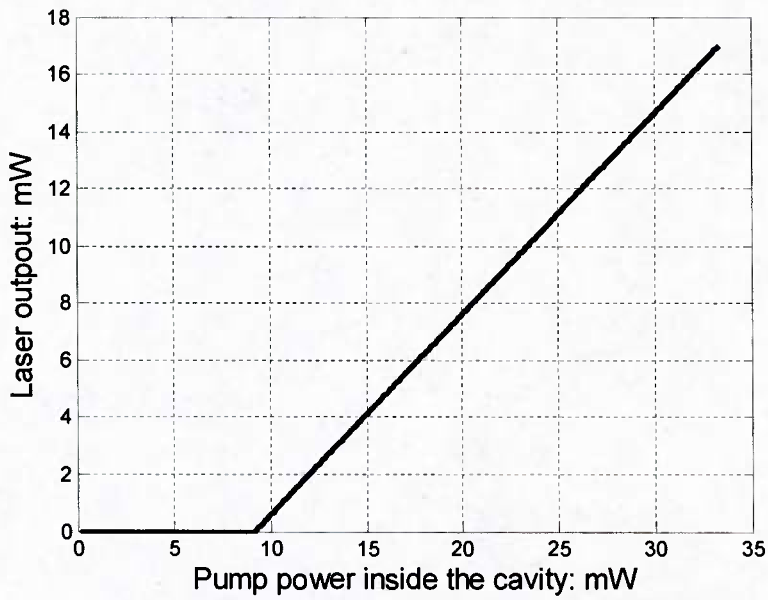


Fig. 12 Laser single mode output vs. input power

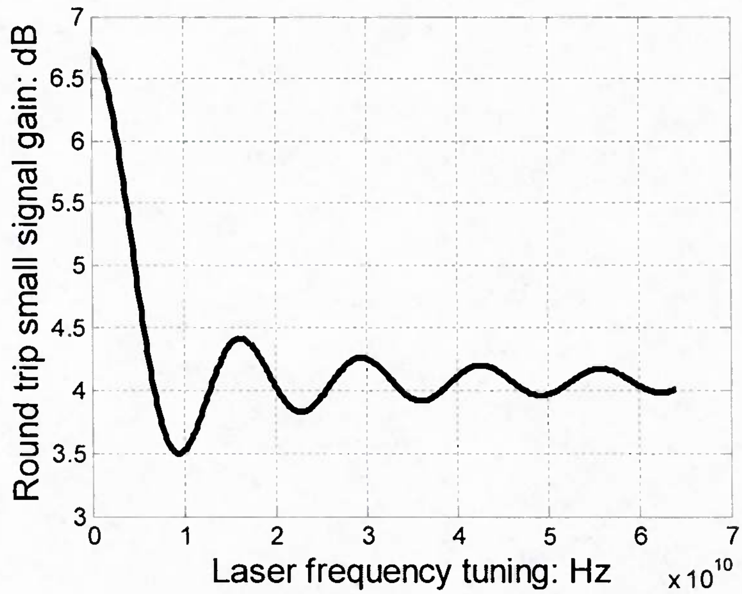


Fig. 13 Frequency selection due to the spatially modulated gain.

The SMG waveguide laser use resonance pumping. The pump sees the same resonate cavity as the 1530nm laser signal. The Fig. 14 shows the pump to cavity coupling ratio as a function of the pump wavelength. The 3dB bandwidth of each resonance window is ~300MHz. At resonance, the pump power inside the cavity is ~1.4 larger than the input pump power.

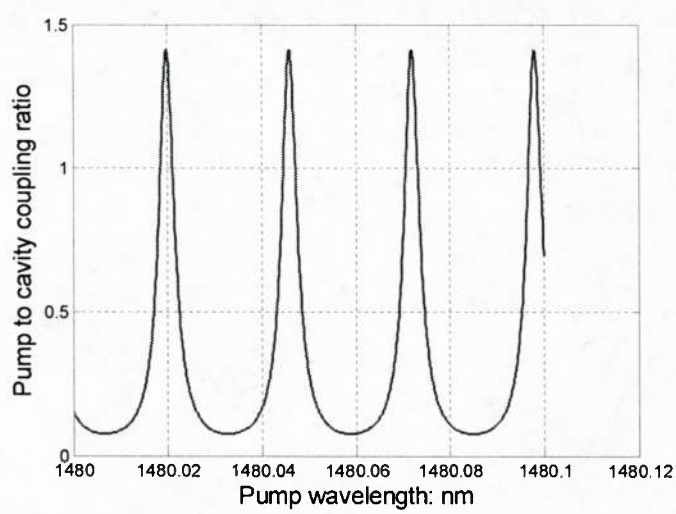
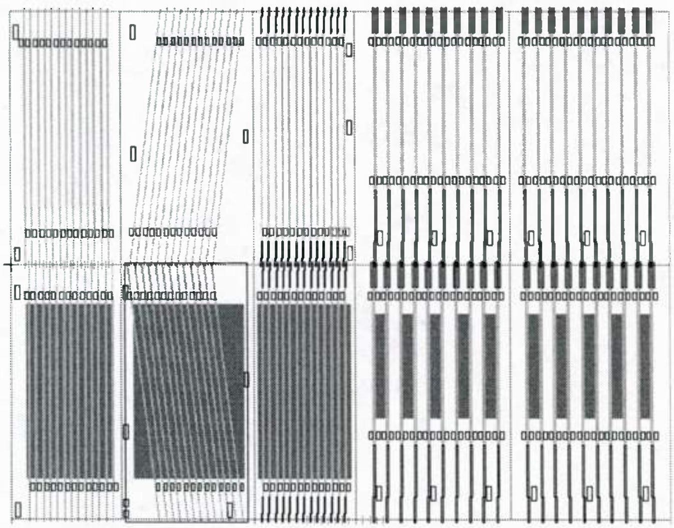


Fig. 14 pump to cavity coupling ratio as a function of pump wavelength during resonance pumping

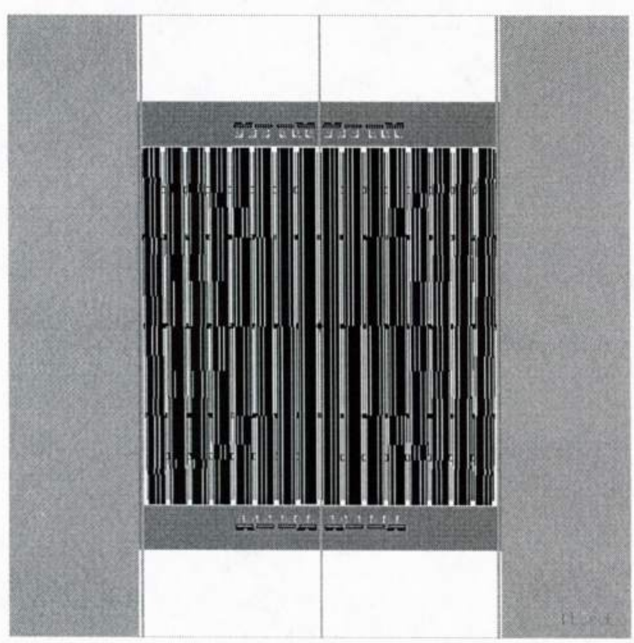
IV. SMG laser fabrication

We designed two mask sets for implementing the SMG laser devices. The first mask set focus on test structures (see Fig. 15a) and the second mask set focus on the actual laser devices (see Fig. 15b). Each mask set contains three main mask layers:

1. Erbium: erbium in-diffusion pattern for defining active gain region
2. Titanium: patterning titanium diffusion pattern for defining low loss optical waveguide
3. Gold: for patterning the electrode



(a)



(b)

Fig. 15 Two sets of mask layouts. (a) test structures; (b) laser devices

We used 2-inch X-cut $LiNbO_3$ wafer from MTI corporation for fabricating the SMG laser device. We performed device fabrication in Harvard University CNS cleanroom. The detailed fabrication process is shown in the Appendix A1. A complete fabrication run involves the following major steps:

- Erbium evaporation
- Wafer dicing
- Erbium diffusion
- Ti in-diffused waveguide
- Device dicing
- Facet polishing
- Mirror coating

4.1 Erbium evaporation

Because erbium is slightly toxic, we cannot evaporate it ourselves using any e-beam evaporator in Harvard University CNS cleanroom. As results, we sent the LiNbO3 wafer to the university of Delaware for Erbium evaporation. In this process step, 220 angstroms of erbium are sputtered to wafer surface.

4.2 Wafer Dicing

The wafer is then diced in order to fit into our diffusion tube furnace (with ~32 mm diameter). To achieve an accurate angle between waveguides and crystal Z-axial, a dicing pattern was firstly defined on the sample using S1805. Then wafer was diced using an automatic dicing saw into one 30 x35 mm sample. Afterwards the photoresist was removed.

4.3 Erbium Diffusion

The wafer is placed inside a tube furnace. The diffusion takes temperature is 1100 degrees and 125 hours with Argon gas flow environment. The thermal diffusion is proceeded and followed by two hours of temperature ramp up and ramp down, respectively. Both are in dry Oxygen gas environment.

After diffusion, the erbium diffused sample was cleaned by piranha etch (H_2SO_4 and H_2O_2). The surface of the sample was checked using atomic force microscopy (AFM) (see Fig. 16).

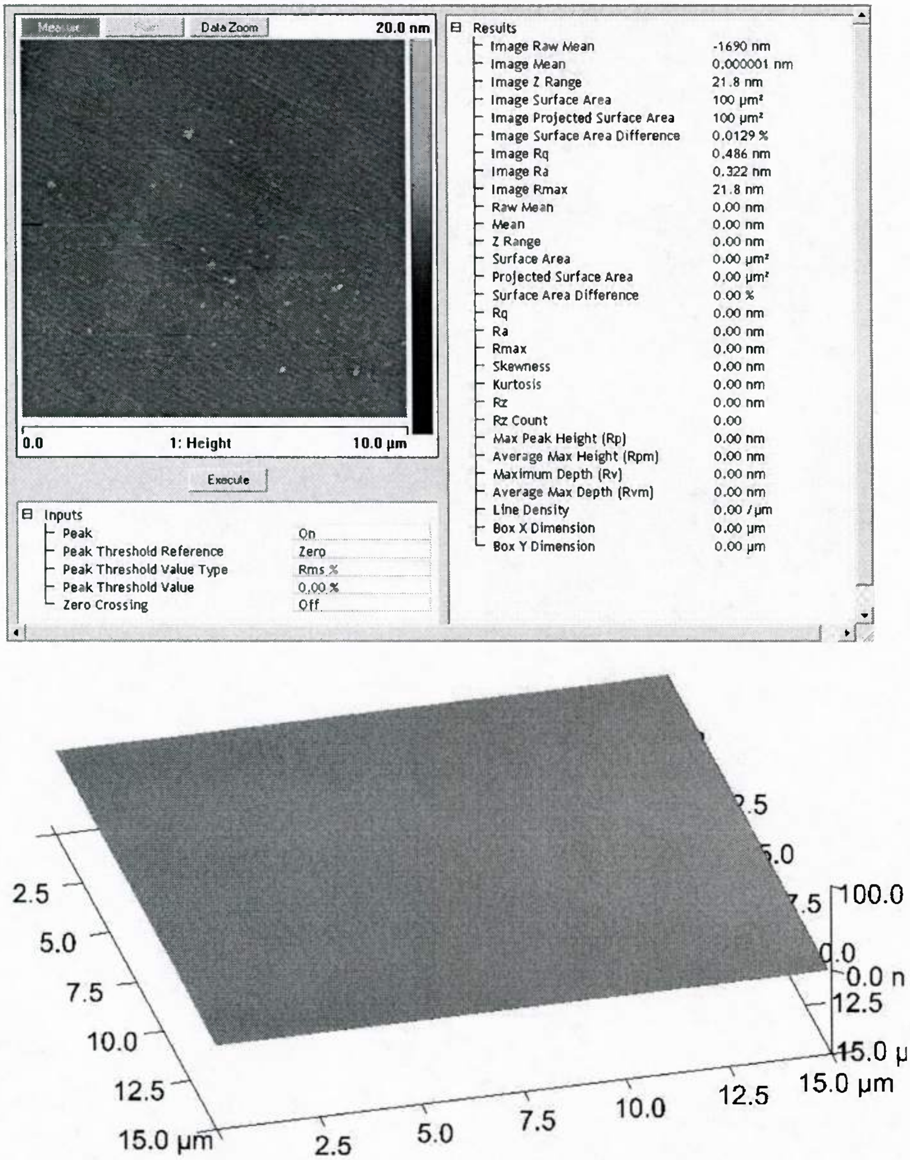


Fig. 16 AFM surface check of Er-diffused sample

4.4 Titanium diffused waveguide

A lift-off process is employed to define Titanium strips on the Erbium diffused sample. The lift-off process is depicted in Fig. 17. The sampled is first spin-coated a LOR 3A layer, and then a S1805 layer. After contact mask alignment and UV exposure, the sample was developed in CD-26. The sample was then checked under an optical microscope (see Fig. 18) for defects. Next, the sample was deposited with 95-nm Ti layer by an e-beam evaporator followed by lift-off inside Remover-PG.

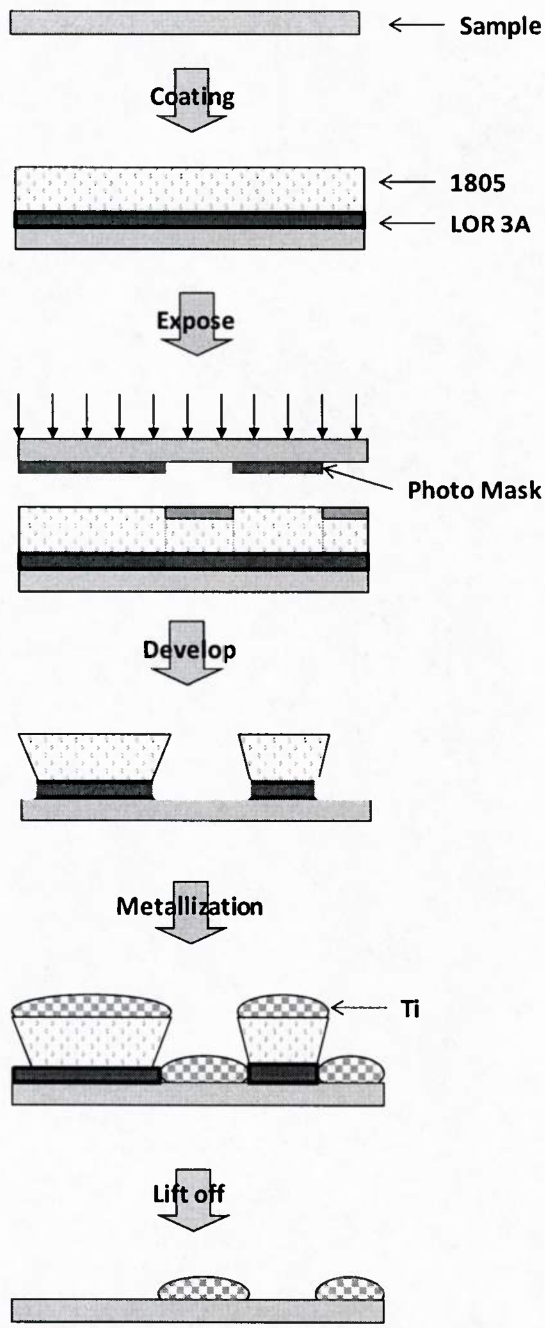


Fig. 17 LOR-3A / S1805 lift-off process

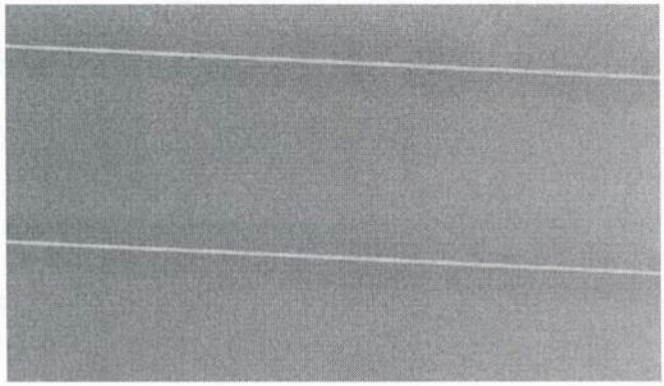
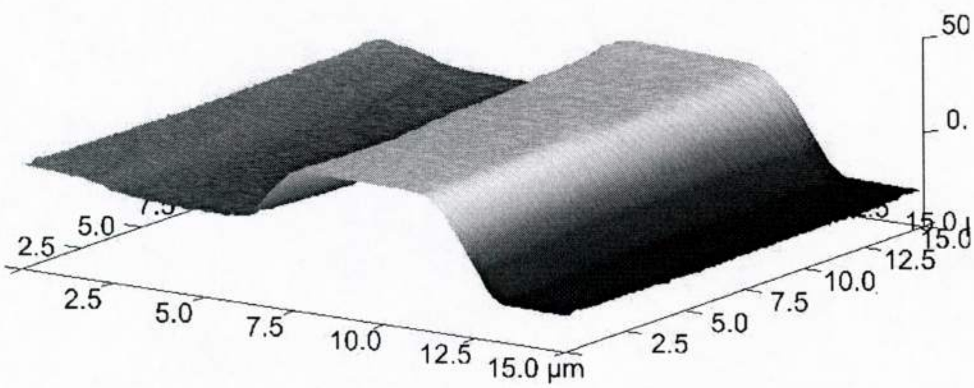
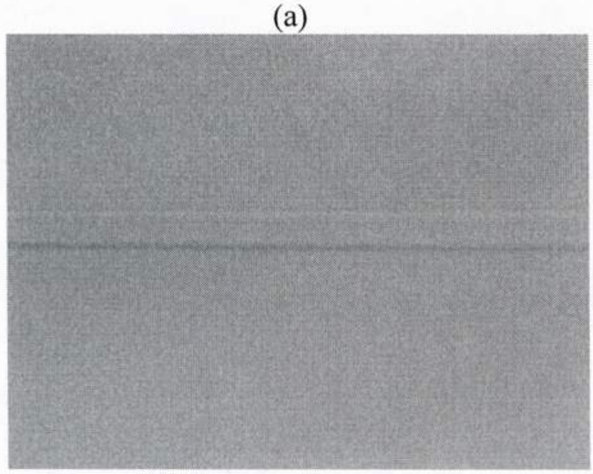


Fig 18 Waveguide pattern after CD-26 development

Next the sample is placed inside a tube furnace for thermal diffusion. The diffusion takes 10 hours inside a Oxygen gas environment. Fig. 19 shows a smooth surface profile and an microscope image of the Ti diffused waveguides.



(a)



(b)

Fig 19 Ti diffused Erbium doped optical waveguide: (a) AFM surface profile; (b) optical microscope image

4.5 Device dicing

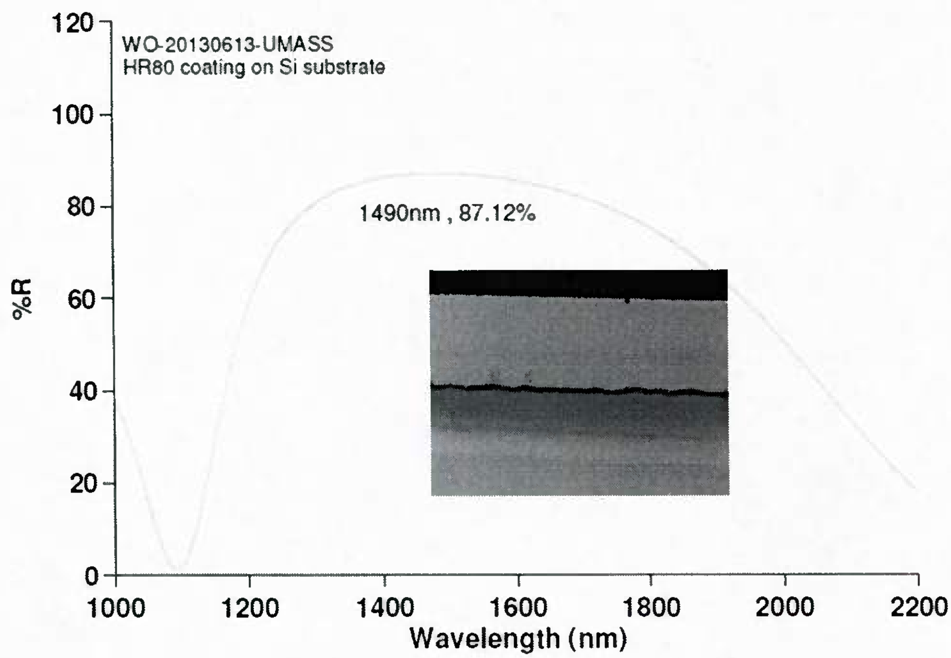
The sample was first evaporated with 1 micron thick SiO_2 film and then bonded to a 1mm thick SiO_2 substrate by crystal bond. The 1micron SiO2 film protects the waveguide during polishing. The 1mm thick SiO2 substrate help maintain current N-face direction during the next polishing step.

4.6 Polishing

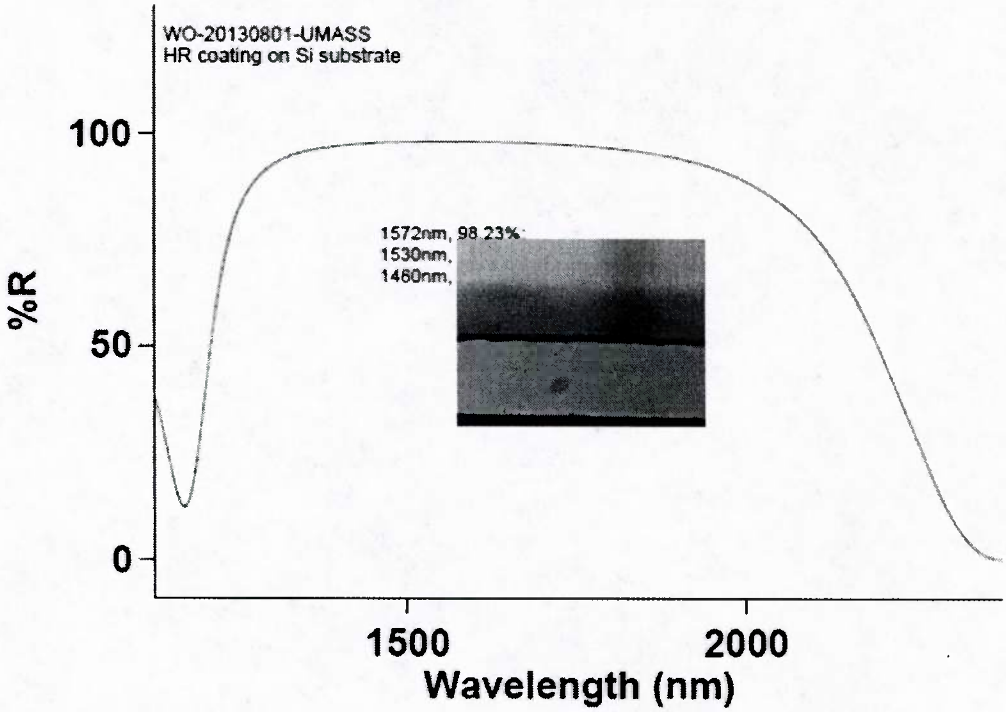
The front end and the back end of the sample are polished to obtain optical grade surfaces for laser mirror coating. Four polishing steps were used. The lapping films for each step are 30 um, 9 um, 1 um, and 0.1 um, respectively. To protect the edges of the both ends, the sample was coated by a layer of S1813 before polish. During the polishing, it is extremely important to maintain the correct n-face direction for minimizing the cavity loss.

4.7 Mirror coating

We outsource the mirror coating step to K-lab. Two dielectric mirrors were evaporated by an e-beam evaporator to the input and output facets of the laser samples, respectively. The input mirror (see Fig. 20a) is our customer designed mirror coating contains five layers of alternating quarterwave (reference to 1490nm center wavelength) SiO_2 and TiO_2 films. The output mirror (see Fig. 20b) is K-lab's standard 1550HR coating. The input mirror has ~80% R for both the laser and pump wavelength. The output mirror has ~98% R for both.



(a)



(b)

Fig. 20 Dielectric mirrors for SMG laser cavities. (a) input mirror; (b) output mirror

V. Measurements

The fabricated SMG waveguide laser samples were comprehensively characterized on the test bench shown in Fig. 21. Three sets of measurements have been performed:

- SMG laser active gain waveguide characterization
- Laser cavity quality factor measurement
- Resonance optical pumping performance

The first two measurements yields the targeted results. In the third measurement we were able to observe strong resonance pumping effects. However, due to lacking of optical pump power we are not able to achieve lasing. This is the biggest disappointment of this project.

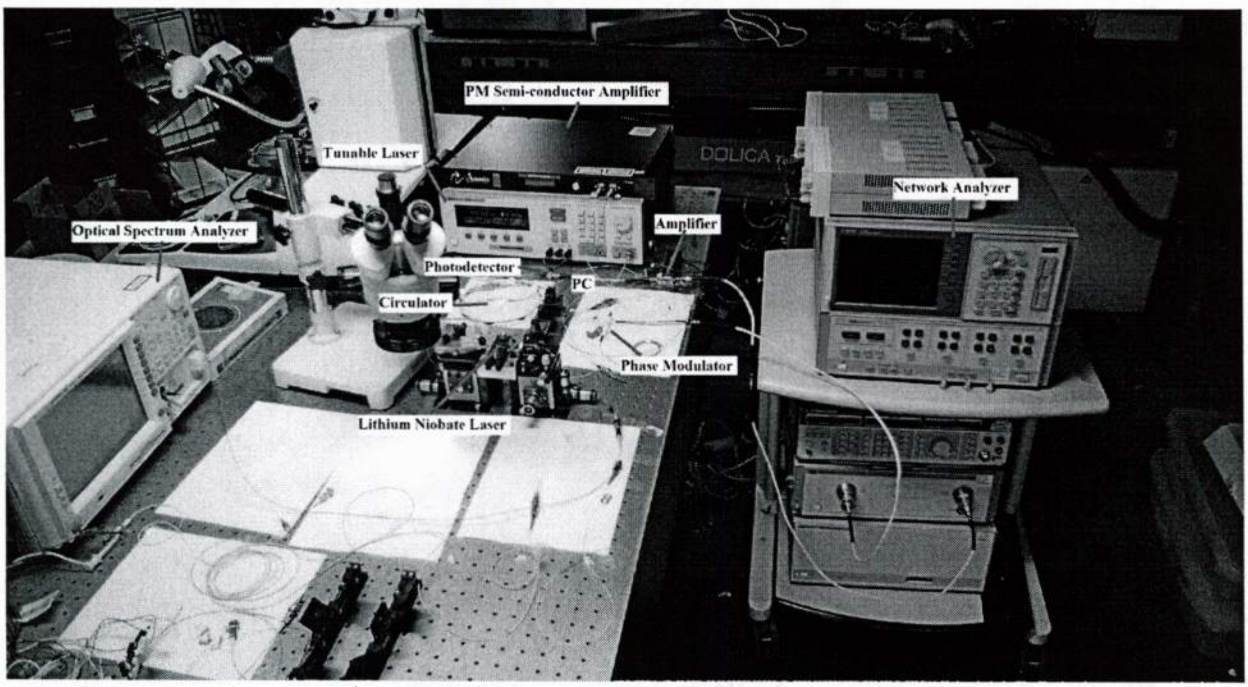


Fig. 21 SMG E/O waveguide laser test bench

5.1 Active waveguide performance

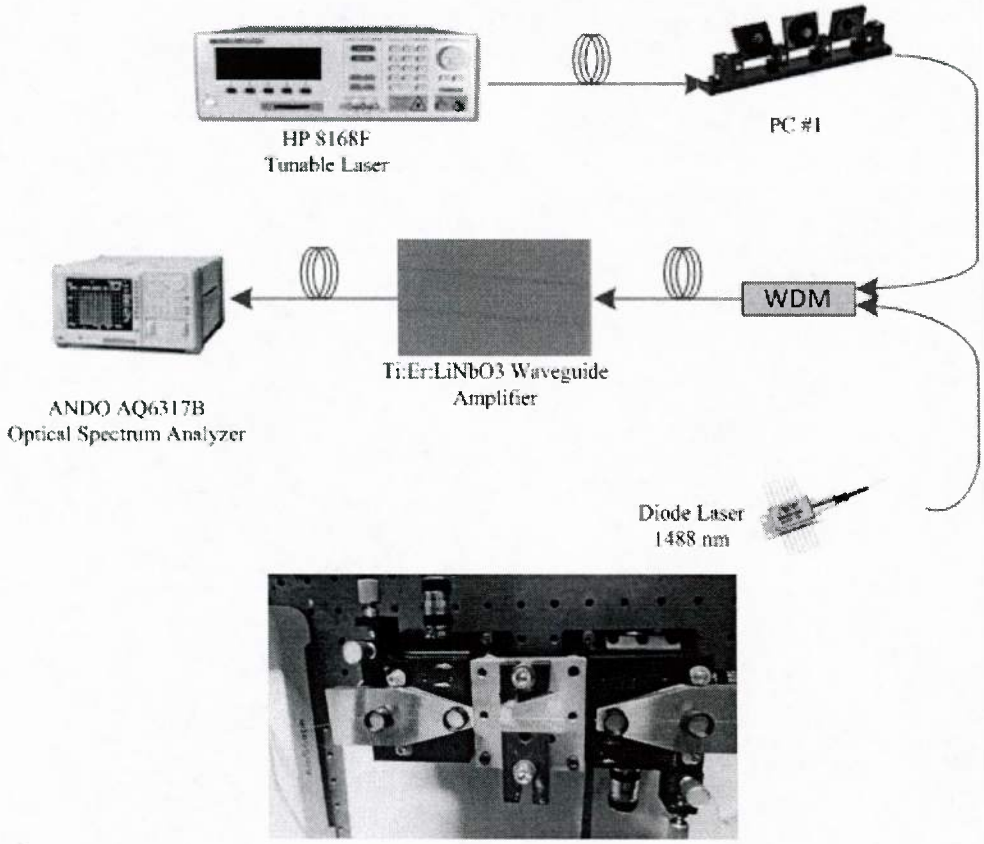


Fig. 22 SMG laser active optical waveguide measurement setup. Here, the laser waveguide is illuminated by a 980nm optical pump beam

Prior to mirror coating, the active waveguide of the SMG laser device is examined by the measurement setup shown in Fig. 22. A tunable laser (HP8168F) is used for the signal source. It combined with an 1480nm pump laser diode through a 1530/1480nmWDM coupler. The combined signal is launched to the Ti:Er diffused optical waveguide by a single mode fiber (SM28). The output signal from the waveguide is coupled back to another optical fiber and analyzed by an optical spectrum analyzer (Ando AQ6317B). The coupling loss from the optical fiber to the laser waveguide is estimated to be around 2dB. Figure 23 shows measured the small signal gain as the function of pump optical power. With 90mW optical input, a small signal gain of 2dB/cm is achieved.

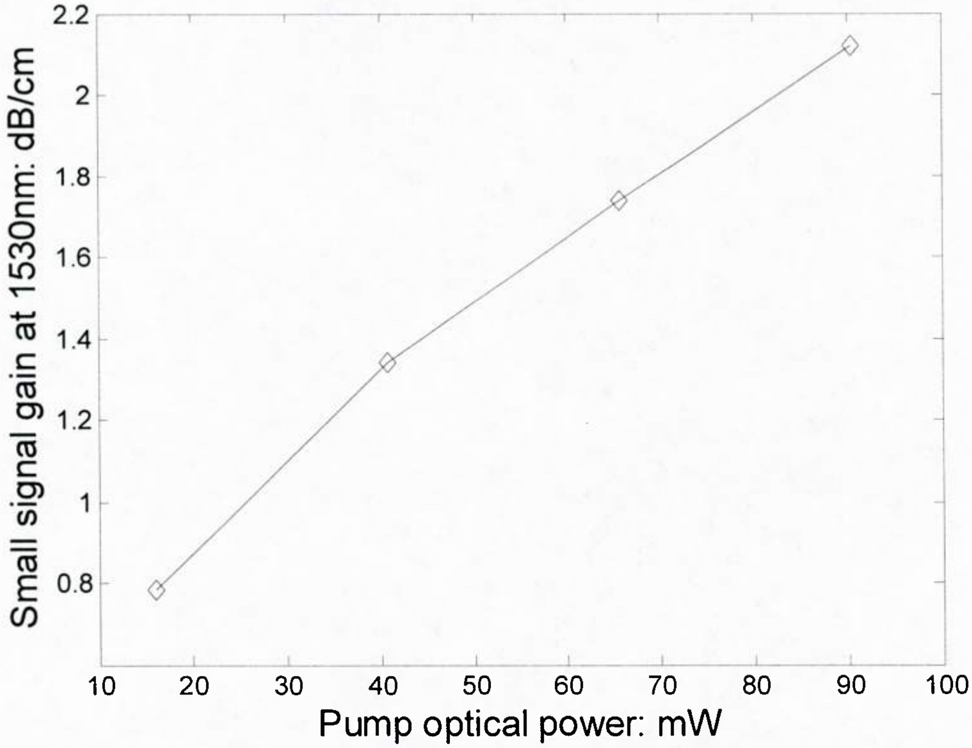


Fig. 23 Measured small signal gain of Ti:Erbium diffused optical waveguide

5.2 Laser cavity quality factor measurement

Next, we measured the laser resonant cavity quality factor for the pump wavelength. The cavity quality factor is determine through using a novel experimental setup (see Fig. 24) employing an optical phase modulator. The single frequency 1480nm optical output from a tunable laser (HP6168F) is first set off - resonance with the laser cavity. Then, it is amplified by an polarization maintaining semiconductor optical amplifier to 16mW. The amplified signal is phase modulated and launched to the laser sample through a polarization maintaining optical circulator. The polarization of the signal is set parallel to the z axis of the LiNbO3 wafer. The reflected signal from the laser sample is first detected by a high speed photodetector, followed by an wideband RF amplifier. A vector network analyzer is used to measure the link transfer function (S21) from the phase modulator input to the RF amplifier output. From the 3dB bandwidth of the measured S21 peak, we detcrmine the quality factor or the round trip loss the of the cavity.

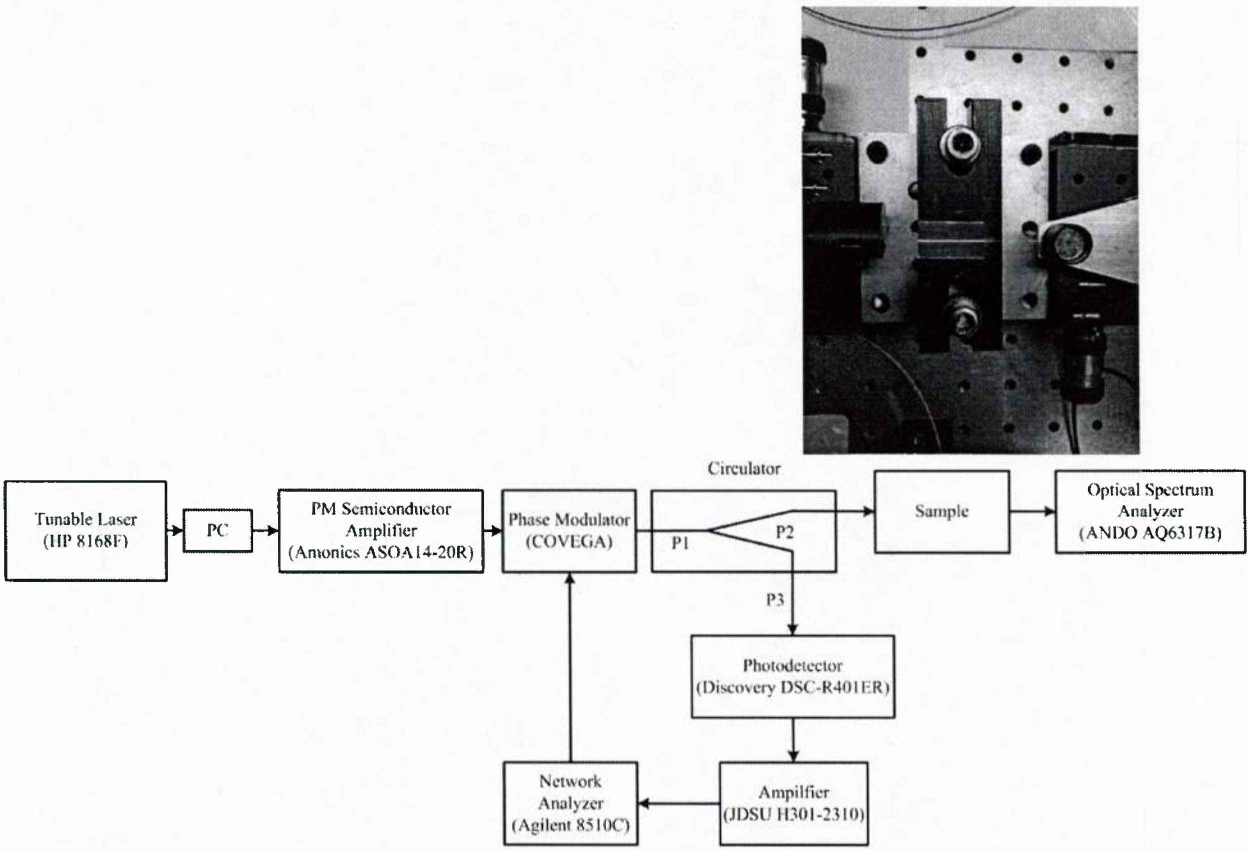


Fig. 24 Laser cavity quality factor measurement.

The measured transfer function (see Fig. 20) shows well-structured resonance peaks. It has a period around 3.8GHz, which corresponds to the free spectra range (FSR) of the 2cm long laser cavity. Within each period, there are two peaks that are caused by the two phase modulation sidebands scanning through the laser cavity resonance. The 3dB bandwidth of the spur is found to be ~250MHz, which corresponds to a cavity round trip loss of 2.2dB. The measured 2.2dB round trip loss includes waveguide absorption, cavity mirror misalignment, and finite mirror reflectivity. It is within the design target (~3dB round trip loss).

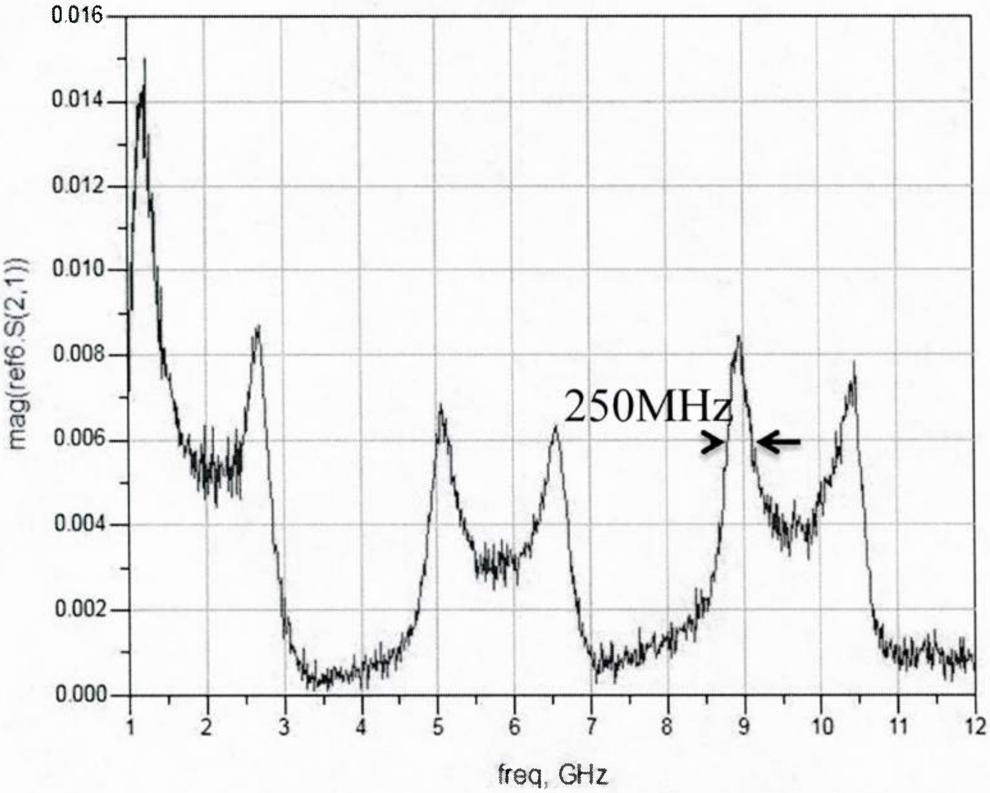


Fig. 20 Transfer function (S21) from phase modulator input to the RF amplifier output

5.3 Resonance pumping

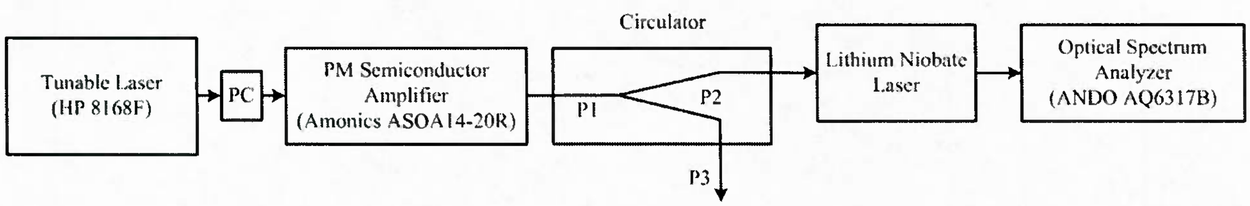


Fig. 22 Resonance pumping setup

We use the same single frequency tunable laser (HP 8168F) for 1480nm optical pumping. The same 1480nm semiconductor optical amplifier is used to boost the pump power to 16mW (see Fig. 22). An spectrum analyzer is used to monitor the transmitted pump power as well as the laser signal.

We observed strong resonance pumping effect. By fine tuning the pump wavelength, we were able to increase the transmitted pump power from -28dBm to -10.3dBm (see. Fig 23). Since the output side of the mirror reflectivity of the laser sample is 98% @ 1480nm, we determine the that pump power inside the laser cavity is ~7dBm (5mW) when the resonate condition is achieved.

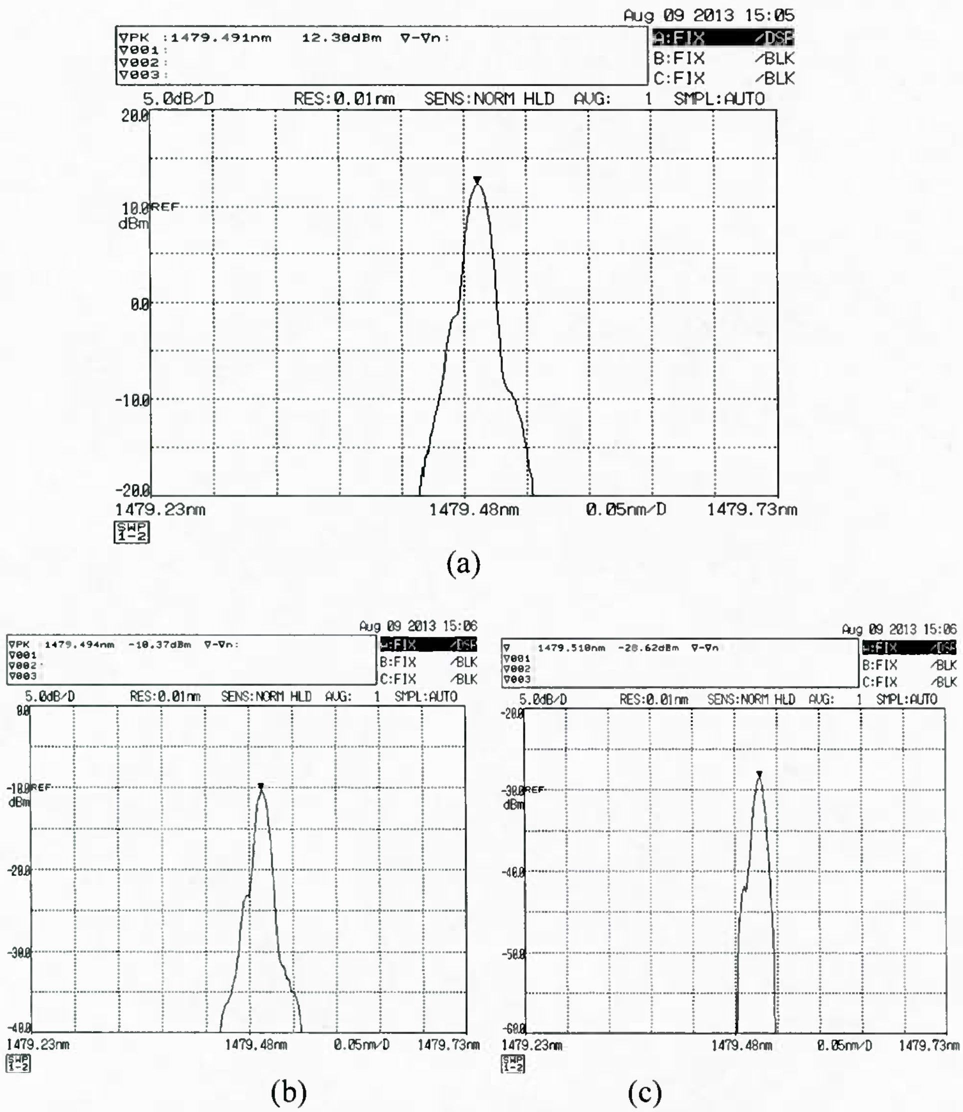


Fig. 23 Resonance enhancement to optical pump. (a) input pump power; (b) output pump power when resonance; (c) output pump power when off resonance

When the pump beam is at the cavity resonance, we observed strong amplified spontaneous emission from the laser sample output (see Fig. 24). However, lasing operation were ultimately limited by maximum power output from the optical amplifier.

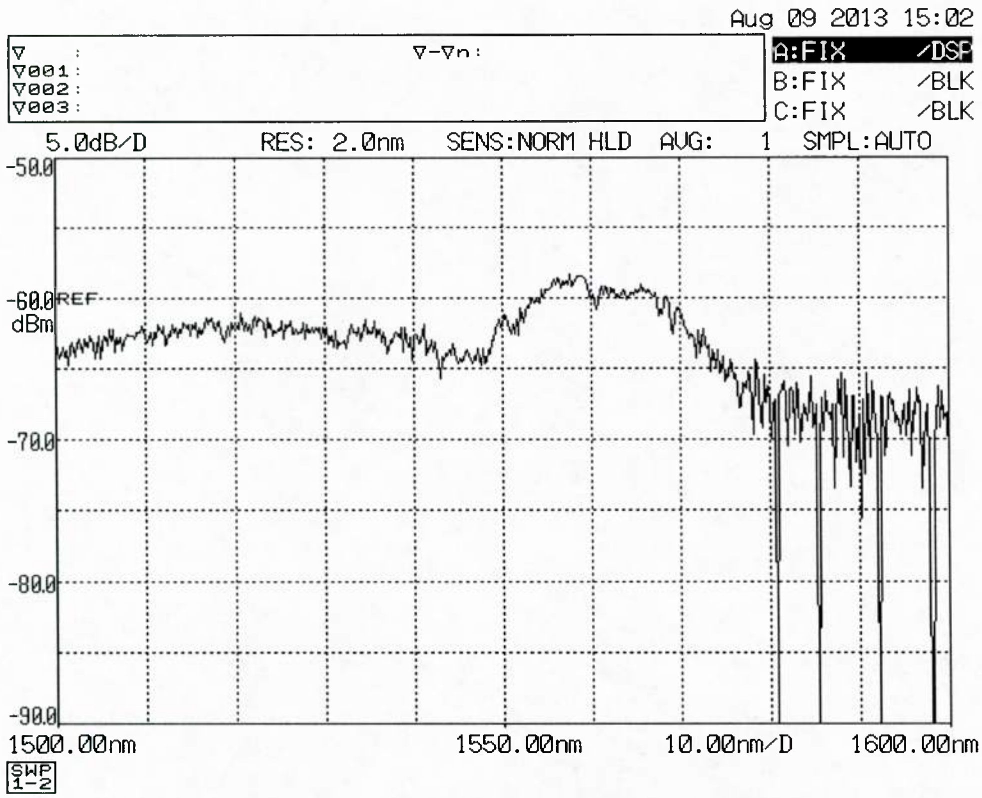


Fig. 24 Amplified spontaneous emission near lasing wavelength

VI. Conclusions and current efforts

In this project we have achieved the following:

- Designed and analyzed spatially modulated gain electro-optical waveguide laser on LiNbO3 substrate. In particular, we devised a novel approach of achieving spatially modulated gain by exploiting optical Birefringence, pump beam standing wave pattern, and resonance pumping.

- Developed the recipe for the SMG laser device fabrication and fabricated complete SMG laser devices using Harvard University CNS clean room facilities

- Comprehensively characterized the fabricated SMG laser devices:
  - Measured over 2dB/cm (with 90mW optical pumping) small signal gain
  - Measured small cavity loss (~2.2dB round trip)
  - Measured strong resonance enhancement to pump coupling (~18dB) to the laser cavity
  - Observed strong amplified spontaneous emission in the laser devices
  - Lasing performance is limited by available pump power

Currently, we are fine tuning laser mirror coating design and improving sample n-face polishing to further reduce the laser cavity loss. In addition, we are trying to get access to a higher pump 1480nm optical amplifier to overcome the pump power limitation.

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Appendix A1.

SMG laser fabrication process flow

Sample Dicing	
Wafer Clean	
	Acetone/IPA/DI water rinse for five minutes
	Dry sample with nitrogen gun
Photoresist Film Preparation	
S1805 coating	spin speed: 5000 rpm/second
	Time: 40 seconds
Hard bake	115 degree for 5 mins in oven
Lithographic Exposure	
Suss MJB4 Mask Aligner	Dose 50 mJ/CM2@ 405nm
	Soft contact
Substrate Development	
CD-26	20 seconds statically, shake the sample gently for 10 seconds
	Soak sample in DI water for one minute
	Dry sample with nitrogen gun
	Check waveguides under microscope
Protection Film Coating	
S1813 Coating	spin speed: 5000 rpm/second
	Time: 40 seconds
Hard Bake	115 degree for 5 mins in oven
	Cool down in room temperature
Dicing	
Automatic Dicing Saw	Blade type: 0.2 mm or 0.3 mm
	Dicing speed: 0.25 mm/s
	Blade height: 0.25 mm
	Tape thickness: 0.5 mm
Erbium Diffusion	
Wafer Clean	
	Acetone/IPA/DI water rinse for five minutes
	Dry sample with nitrogen gun
Diffusion	
Furnace	1100 degree for 125 hours in Argon
	Warm up and cool down for two hours respectively in Oxygen

Wafer Clean	
Pirana etch	H_2SO_4:H_2O_2 (3.5:1)
	Rinse for 10 mins at 80 degree
	Rinse into DI water for 5 mins
	Dry by Nitrogen gun
Photolithography	
Wafer Clean	
	Acetone/IPA/DI water rinse for five minutes
	Dry sample with nitrogen gun
Photoresist Film Preparation	
LOR 3A Coating	spin speed: 4500 rpm/second
	Time: 40 seconds
Hard Bake	180 degree for 120 seconds in oven
S1805 Coating	spin speed: 5000 rpm/second
	Time: 40 seconds
Hard bake	115 degree for 5 mins in oven
Lithographic Exposure	
Suss MJB4 Mask Aligner	Dose 80 mJ/CM2@ 405nm
	Soft contact
Substrate Development	
CD-26	30 seconds statically, shake the sample gently for 15 seconds
	Soak sample in DI water for one minute
	Dry sample with nitrogen gun
	Check waveguides under microscope
Titanium Deposition and Lift-off	
Descum	
Anatech Barrel Plasma System	O_2: 40 sccm
	RF power: 75 w for 20 seconds
Metal Deposition	
EE-3 Sharon Evaporator	Voltage: 10.5 V; current: 0.05 A
	Rate: 0.8 A/s~ 1A/s
Lift-off	
Remover-PG	Rinse for 15 mins at 80 degree
	Ultrasonic for 3 mins
	Rinse for 10 mins at 80 degree
IPA	Rinse in IPA for 5 mins
DI	Rinse in DI for 5 mins

Titanium Diffusion	
Wafer Clean	
	Acetone/IPA/DI water rinse for five minutes
	Dry sample with nitrogen gun
Diffusion	
Furnace	1050 degree for 10 hours in Oxygen
	Before diffusion, dry the tube using Nitrogen for one hour, and the relative humidity is around 20%
	Warm up and cool down for one hour and hours respectively in Oxygen
Wafer Clean	
Pirana etch	H2SO4:H2O2 (3.5:1)
	Rinse for 10 mins at 80 degree
	Rinse into DI water for 5 mins
	Dry by Nitrogen gun
Polish	
Protection Film Coating	
NEXX PECVD	Recipe name: "SiO2HR"
	Thickness: 1 um
	Temperature: 20 degree; deposit rate: 20 nm/min
Glass Coverage	
	Cover the surface of the sample with a 1 mm thick glass wafer using crystal bonder at 110 degree.
Automatic dicing saw	Dice the sample together with the bonded glass sample
	Apply a little epoxy on the interface of LiNbO3 and glass
	Now the sample is ready to be polished. Both the SiO2 and glass will protect the edge of the sample.
Polish	
Polisher	Fix sample on the holder using wax (heating at 120 degree). Due to the employment of epoxy, there will be no movement between LiNbO3 wafer and glass.
Lapping film	30 um, 9 um, 1 um, and 0.1 um
Wafer Clean	
	Remove the LiNbO3 sample from glass by dipping the it into Acetone for 30 mins
	IPA/DI water rinse for five minutes
	Dry sample with nitrogen gun
	Check the polish quality under microscope